N90-28296

REMOTE SOUNDING THROUGH SEMI-TRANSPARENT CIRRUS CLOUD

William L. Smith, Steven A. Ackerman, and Allan H.-L. Huang

Cooperative Institute for Meteorological Satellite Studies
Space Science and Engineering Center
1225 West Dayton Street
Madison, Wisconsin 53706

1. Introduction

A large part of the earth is covered by thin semi-transparent cirrus cloud (Wylie et al., 1989). The cirrus results from the natural injection of moisture into the upper troposphere by deep convection (i.e., anvils) and from man-made moisture injected into the upper troposphere by jet aircraft. Although most cirrus cloud is semi-transparent to infrared wavelengths, their heights, thicknesses, and spectral absorption properties must be known in order to retrieve atmospheric temperature and moisture profiles from the data.

In this paper, an algorithm is developed for accounting for the radiative properties of semi-transparent cloud in the retrieval of vertical temperature and moisture profiles. The algorithm is to be applied to the NASA ER2 HIS data collected during the FIRE cirrus field program. The results of its application will be reported at the second FIRE Annual Meeting to be held July 10-14, 1989 in Monterey, California.

2. The Cloud Algorithm

The retrieval of temperature and moisture profiles from spectral measurements of upwelling radiances are most efficiently achieved through the simultaneous solution of the radiative transfer equation of the form (Smith et al., 1989)

$$\delta I(\nu_j) = \delta T_s f_j^o \tau_s(\nu_j^o) - \sum_{i=1}^{N} \int_{p^*}^{p_s} \delta T_i(p) f_j^o \tau^o(\nu_j) \frac{d\ln \tau_i^o(\nu_j)}{dp} dp \qquad (1)$$

where I is spectral radiance, ν is wavenumber, T is temperature, f is the derivative of Planck radiance with respect to temperature computed for a "guess" temperature profile condition, τ^o is the total atmospheric transmittance (i.e., the transmittance due to all absorbing constituents) for the "guess" atmospheric conditions, τ_i^o is the transmittance due to individual absorbing constituents (e.g., CO_2, H_2O, and cloud). The subscript "s" denotes the surface value, N the number of individual absorbers to be considered, and the transmittance function is understood to pertain to the atmosphere between the instrument level (p*) and the level of interest (p).

The symbol δ denotes a perturbation from the "guess" condition. For a constituent whose concentration is known apriori, δT_i represents the deviation of the actual temperature profile from the "guess" profile. For all other constituents,

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$$\delta T_i = \delta T - \frac{\partial T}{\partial U_i^o} (U_i - U_i^o) \tag{2}$$

where $\delta T = T - T^o$, U_i is the total path length of the gas between the instrument and the level of interest. The significance of Eq. (1) is that it is linear, the only unknowns are the temperature perturbations, $\delta T_i(p)$ and they can be determined by the linear inverse of (1).

Neglecting scattering, clouds can be treated in the very same manner as a molecular absorber, provided its spectral dependence is known. In this case, the total transmittance $\tau^o(\nu_j)$ is given by

$$\tau^o(\nu_j) = \prod_i \tau_i^o(\nu_j)$$

where the "guess" cloud transmittance (e.g., i=3) has the form

$$\tau_{cd}(\nu_j) = \tau^o{}_3(\nu_j) = \mathrm{EXP}\ \{ -\alpha\ f(\nu_j, r^o) \left(\frac{p - p_t}{p_b - p_t}\right) \} . \tag{3}$$

In (3), α is a constant dependent upon the total ice or water content of the cloud, $f(\nu, r^o)$ is a spectral function dependent on the effective radii, r^o, of the absorbing particles (ice or liquid water drops), P_t and P_b are the top and base pressures of the cloud. Assuming that the cloud is purely absorbing, a good approximation for $f(\nu, r^o)$ can be obtained by the Modified Anomalous Diffraction Theory (MADT) presented by Ackerman and Stephens (1987). In this case,

$$f(\nu, r^o) = Q_{ABS} = 1 + \frac{m^2}{2\chi n_i} e^{-4\chi n^i} \left(1 + \frac{1}{4\chi n_i}\right) - \frac{m}{2\chi n_i} e^{-4\chi n_i \sqrt{1 - m^{-2}}} \left(\sqrt{m^2 - 1} + \frac{m}{4\chi n_i}\right) \tag{4}$$

where Q_{ABS} is the absorption efficiency, χ is the size parameter $2\pi r^o/\lambda$, where r^o is the effective particle radius and λ is the wavelength, m is the index of refraction, and n_i is the complex part of the index of refraction. Figure 1 shows a comparison between the absorption efficiency computed for ice clouds using modified anomalous diffraction theory and Mie theory. It can be seen that the difference in spectral dependence for large and small particles is explained with MADT. In fact, if the effective radius is a free parameter, as it is in the retrieval problem, an effective radius for Eq. (4) can be chosen which provides an even closer fit to the Mie calculations.

Thus, given (3) and (4), one has the following four cloud parameters, α, r^o, P_t, and P_b. If we consider the cloud term of Eq. (1), we can write

$$- \int_{p^*}^{P_s} \delta T_{cd} \tau^o(\nu_j) \frac{d\ln \tau_{cd}(\nu_j)}{dp} dp = \beta^o f(\nu_j, r^o) \int_{p^*}^{P_s} \delta T_{cd} f_j \tau^o(\nu_j) dp \qquad (5)$$

where $\beta = \alpha/(P_b - P_t)$. Thus, given an initial guess of α, r^o, P_t, and P_b from which $\tau^o(\nu_i)$can be specified, one could solve for the profile

$$\delta T_i = \delta T_{cd} = (T_{cd} - T) \ . \qquad p_t \le p \le p_b$$

As with the molecular absorber

$$T_{cd} - T = - \frac{\partial T}{\partial U_{cd}^o} (U_{cd} - U_{cd}^o)$$

Since

$$U_{cd} = \beta(p - p_t)$$

Then,

$$T_{cd} - T = - \frac{\partial T}{\partial p} \left[\delta\beta \left(\frac{p - p_t{}^o}{\beta^o}\right) - \delta p_t \right] . \qquad (6)$$

If the true temperature profile, T, and the cloud temperature profile, T_{cd}, are known from the increase solution of Eq. (1), Eq. (6) can be solved for $\delta\beta$ and δp_t. Given $\delta\beta$ and δp_t, a new base pressure can be defined from

$$p_b \approx p_t + \frac{\alpha^o}{\beta} = (p_t{}^o + \delta p_t) + \frac{\alpha^o}{\beta^o + \delta\beta} \quad . \qquad (7)$$

The solution for the absorber temperature profiles and cloud parameters depend upon an initial estimate of the particle radius r^o and the particle concentration variable α^o. It can be shown that for an isothermal cloud, and at a wavenumber void of molecular absorption (i.e., a "window")

$$f(\nu_o, r^o)\ \alpha^o = \ln \left\{ \frac{I(\nu_o) - B[T^o(p^o{}_t)]}{B(T_s{}^o) - B[T^o(P^o{}_t)} \right\} . \tag{8}$$

In order to solve (8) for r^o and α^o, the initial cloud top pressure can be defined using the CO_2 slicing technique (Menzel, 1986; Smith and Frey, 1988). Given the product $f(\nu_o, r^o)\alpha^o$ for two window wavelengths whose cirrus optical properties are expected to differ (e.g., 8.5 and 11.5μm as shown in Fig. 1), r^o can be defined from the ratio of Eq. (8) applied to the two wavelengths since α^o cancels. Once r^o is known, α^o can then be obtained from Eq. (8) applied to either one of the two window wavelengths. Given α^o an estimate of β^o can be obtained from an initial guess of cloud-base altitude, $p_b{}^o$ (i.e., $\beta^o = \alpha^o/(p_b{}^o - p_t{}^o)$).

In summary, the following steps can be taken to solve simultaneously for temperature and water vapor profiles and cloud parameters from cirrus cloud contaminated radiance spectra:

(1) Using the CO_2 slicing technique with the guess temperature profile, solve for an initial cloud top pressure, p_t^o.

(2) Using the 8.5μm and 11.5μm window radiances and the initial guess surface and cloud temperature conditions, use Eq. (8) to determine the ratio $f(8.5\mu m,\ r^o)/f(11.5\mu m,\ r^o)$. Use (4) to determine r^o and then Eq. (8) applied to one of the two window wavelengths to determine α^o. This step yields the initial guess cloud parameters α^o, β^o, $p_b{}^o$.

(3) Specify the initial guess cloud transmission profile using Eq. (3) where $f(\nu_j,\ r^o)$ is calculated using Eq. (4).

(4) Solve for the profiles δT_i through the linear matrix inverse solution of Eq. (1).

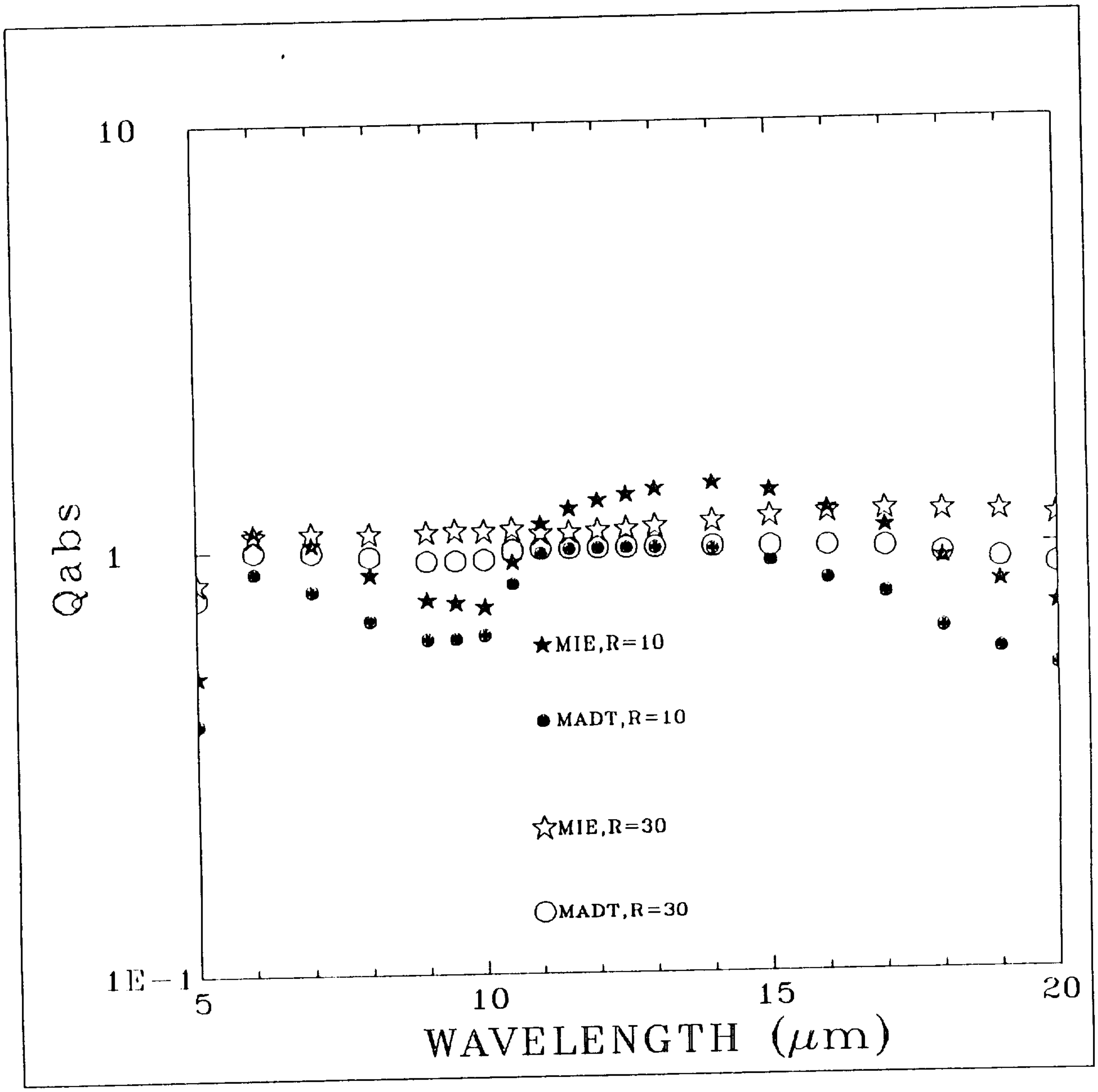
(5) Use Eq. (6) to solve for $\delta\beta$ and δp_t.

(6) Use Eq. (7) to provide p_b.

The entire process could be iterated until the cloud parameters cease to change from one iteration to the next.

3. Summary

A method for direct and simultaneous solution for temperature and moisture profiles and cloud parameters is outlined. The method takes into account the spectral dependence of cloud emissivity/transmissivity which has been found to be a function of particle size. The results of the application of this technique to cirrus radiance spectra achieved with the HIS interferometer flown on the NASA ER2 during the FIRE will be reported at the meeting.


10
Qabs
1
1E-1
5
10
15
20
WAVELENGTH (μm)
MIE,R=10
MADT,R=10
MIE,R=30
MADT,R=30